NIST First Quarter Progress Report
Home Smoke Alarm Research Project

Progress on Planned Tasks

There were four tasks scheduled for the first quarter of the project. The status of each is discussed below:

1. Acquire test detectors/alarms and conduct detector characterization.   Months 1-3
The NIST project staff will meet with smoke alarm manufacturers and develop a set of test articles that are representative of the range of products currently sold. Appropriate modifications may be made to the test articles to facilitate the acquisition of useful data but any modified articles will be calibrated against unmodified devices to assure representativeness. All test articles will be initially characterized in NIST's FE/DE apparatus to provide baseline data. Test articles exposed to fire tests will be re-checked in the FE/DE between field trials to assure that such exposure did not alter the operational characteristics.
$90k

> The meeting was held at NIST and was attended by Larry Ratzlaff of Kidde, Tom Barakat of Maplethorpe and Mark Devine of First Alert. Arthur Lee of CPSC also attended. At this meeting it was decided that each manufacturer would provide 12 examples each of their current ionization, photoelectric, and CO sensors modified for analog output. This modification will provide for the continuous recording of sensor signal during tests that will allow the determination of potential performance improvements from different alarm threshold settings and the potential performance of combined sensors with some alarm algorithm. The downside is that the test samples will not be identical to commercially available units. However, NIST will be characterizing every test sample in the FE/DE and this will allow the verification of the analog output level that results in an alarm from unmodified units. Given the value of the information and the ability to independently verify the performance against unmodified units it was decided that this approach would be taken.

> A target schedule for delivery of the test examples was established as October 1 for the ionization samples, November 1 for the CO, and December 1 for the photoelectric (these are the most difficult to modify because of the pulsed optics and IC circuitry). As of this writing, NIST has received two sets of ionization and one set of CO samples. First Alert decided that they would provide a new model combination ion/photo unit with independent analog outputs from each sensor. This delayed their availability to January and coincides with the promised delivery of the Kidde photo units. Even if some units do not arrive until February the schedule will not be affected.

> Tom Cleary developed a testing plan (see Attachment A) for the FE/DE characterizations that will provide enough replicates to statistically determine the repeatability of the alarm threshold readings for each unit. This will also provide error bounds on the analog output signal. Tests on the samples in hand are nearly completed.

2. Identify potential dwellings for test sites   Months 1-3
Test sites must be typical of US housing and represent single- and multi-family units, apartments
and condominiums, and manufactured homes. Test sites will be selected from donated homes
scheduled for demolition or rehab, purchased units, or simulated arrangements of rooms.
Potential sites will be identified and evaluated by NIST staff and selections made in the interest
of the overall project goals.
$25k

> Homes at several locations, Orange County California and British Colombia Canada,
> were evaluated and rejected for various reasons. Homes in North Carolina appear to be
> suitable but more evaluation is being made against specific criteria such as a single floor,
> split level, and two story, about 1200 square feet, and 800 square feet per floor
> respectively, no major breaches in interior and exterior walls, and working utilities. We
> expect to have specific homes identified by mid-January.

3. Plan for long term site at NIST   Months 1-3
One of the test sites will be a manufactured home to be purchased and located at the NIST site
for the duration of the work. An appropriate floor plan has been chosen and a unit will be
procured and installed on the site.
$50k

> As planned a new 3-bedroom manufactured home to be located at NIST and used for
> both fire performance and nuisance alarm tests was identified and the procurement
> process initiated. We expect delivery in late January or February so that instrumentation
> can proceed. Testing could begin as early as March as appropriate. The manufactured
> home is being provided by a local dealer at his cost (approximately $17,000).

4. Review NFIRS data and develop scenarios (NFPA)   Months 1-3
For the test scenarios to be realistic they need to be based on current, fatal residential fire
scenarios in terms of such parameters as ignition source and first item ignited, room of origin,
location of occupants and time of day. Dr. John Hall will conduct an analysis of the latest five
years of NFIRS data to develop the test scenario descriptions. This work is being conducted by
NFPA as an in-kind contribution to the project.

> Dr. Hall reports that the scenario analysis done for the CPSC Round Table effort is still
> valid and should be used. Thus, this task is complete and will use the report in hand.

In addition, initial work on task 6 was completed with the development and distribution for
comment of a Measurement and Data Analysis Plan (see Attachment B). This document has
been useful in communicating to participants and others interested the types of data that will be
produced in the experiments and for planning for the availability of resources at the test sites.
We have further confirmed the participation of the National Research Council of Canada who
will provide quantitative FTIR measurements and analysis of second and third tier gases during
the experiments. The Measurement and Data Analysis Plan has been helpful in identifying the
specific gases and the desired resolution of their measurement.

During this quarter an opportunity to collaborate with another NIST project has presented itself. NIST is serving as project manager for a consortium-sponsored project organized through the NFPA's Fire Protection Research Foundation examining sub-lethal effects of combustion toxicity. The initial phases of this project have involved a very detailed literature review and computational analysis. Another task is to perform a series of full-scale fire experiments in residential geometries and with residential fuels that are quite similar to the experiments planned for the smoke alarm project. Their budget for the experimental task is approximately $500k. Thus we have been discussing the advantages and disadvantages of combining the programs.

Their plan was to take all experiments through flashover since variations in ventilation has such a large impact on toxic species production. We had planned to do some flashover experiments but these would be limited because of the additional expense of hardening the test sites. Combining the projects would allow the Toxicity project to pay for the hardening and provide the opportunity to do many more flashover experiments (as Dr. Hall argued for in the initial Steering Committee meeting). Their goals require more control over the selection of materials for the fuel items than we would require. This would require that furniture be purchased new rather than used as we had planned, but their project would bear these costs. The advantage to us is better knowledge of the combustion chemistry for both modeling and data analysis. Both projects were planning the experiments to be conducted over the same time period. Thus, at present it appears that there is much to be gained and little to be lost in combining forces with the other project. Discussions continue, and I will arrange a presentation on the toxicity project for the Steering Committee meeting on February 1 after which we can decide whether or not to proceed.

Attachment A
**Calibration of modified, analog-output
residential smoke detectors and CO detectors.**

The modified residential smoke detectors and CO detectors will be calibrated against steady smoke and CO concentrations in the fire emulator/detector evaluator. Each smoke detector will be subjected to repeated flaming smoke (soot) and cotton smolder smoke exposure tests. In these tests, the smoke concentration is increased in a stepwise fashion. The detector output is compared to the steady- smoke level at each step. Both smoke obscuration and MIC readings are gathered. Smoke obscuration measures are appropriate for photoelectric detector calibration, while MIC measures are more appropriate for ionization detector calibration. Each detector will be exposed to each smoke twice before field tests, and once after field tests to check if any calibration shift has occurred.

The flaming smoke is generated from the propene diffusion flame burner attached to the FE/DE. During an exposure test, the flow velocity is fixed at 20 cm/s and smoke concentration is increased by increasing the fuel flow to the burner and opening the damper from the burner to the FE/DE duct. Each step is held for a period of time to allow for the light extinction to achieve a nearly steady value. The smolder smoke is generated from a wick smoldering fixture designed for the FE/DE. Again, the flow velocity is fixed at 20 cm/s and wicks are ignited (smoldering) at different time steps to produce stepwise increasing smoke concentrations in the FE/DE. At the test section, the temperature rise is at most 3 ^{O}C during any of these exposure tests. Figure 1 shows the light transmission across the duct, the MIC output, and the voltage output from a residential ionization detector. Figures 2 and 3 show calibration curves obtained from two separate flaming and smolder smoke exposure tests with the same detector. A statistical comparison of the slope and intercept of repeated runs using analysis of covariance or other suitable techniques will provide a quantitative assessment of the detector calibration before and after field testing.

Detector # 14 - Cotton Smolder

y = 0.059136 - 38.57x R= 0.99928
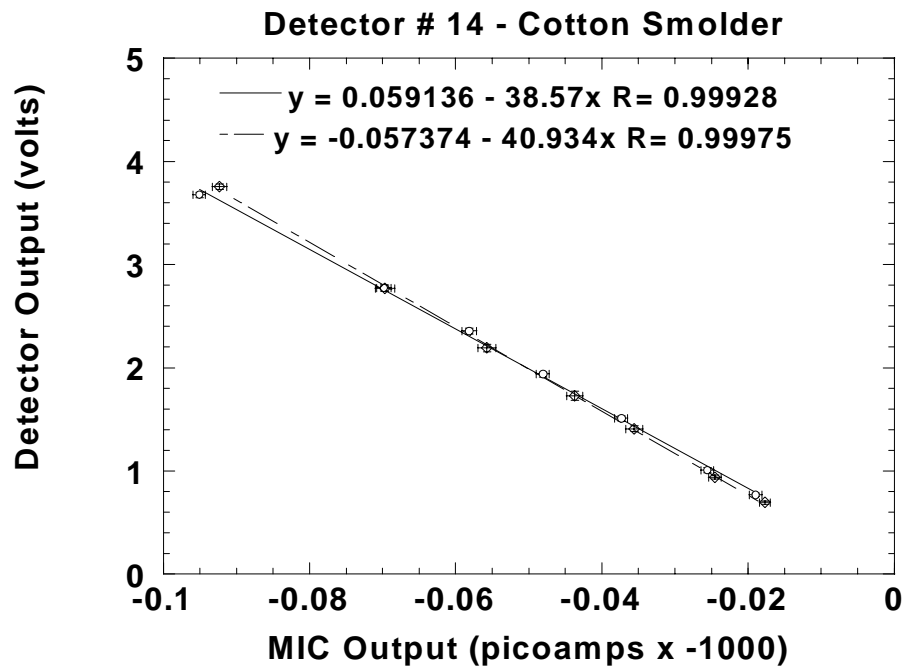y = -0.057374 - 40.934x R= 0.99975

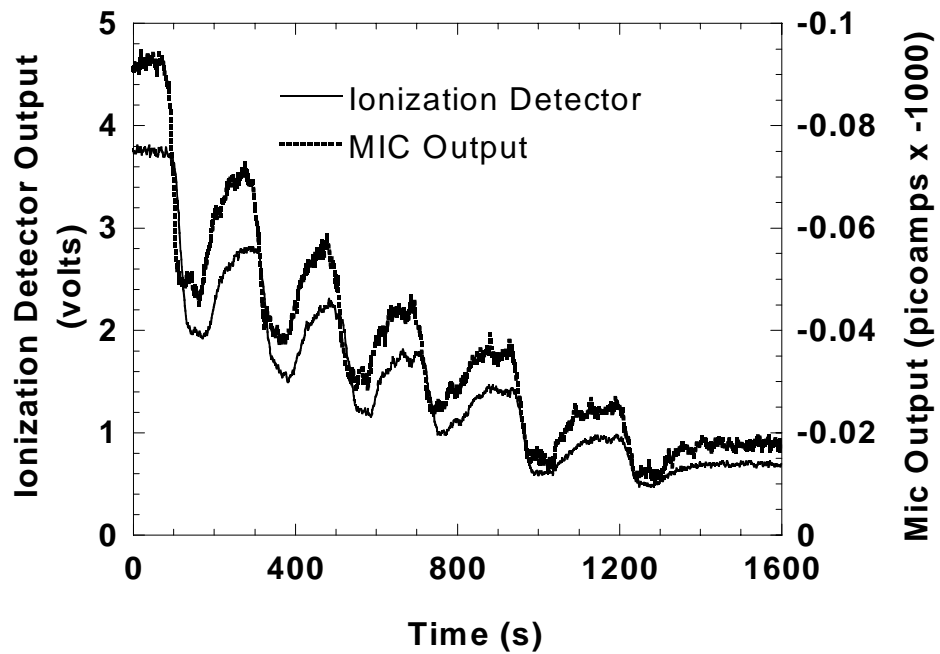Figure 1. Ionization detector calibration run for smolder smoke exposure.

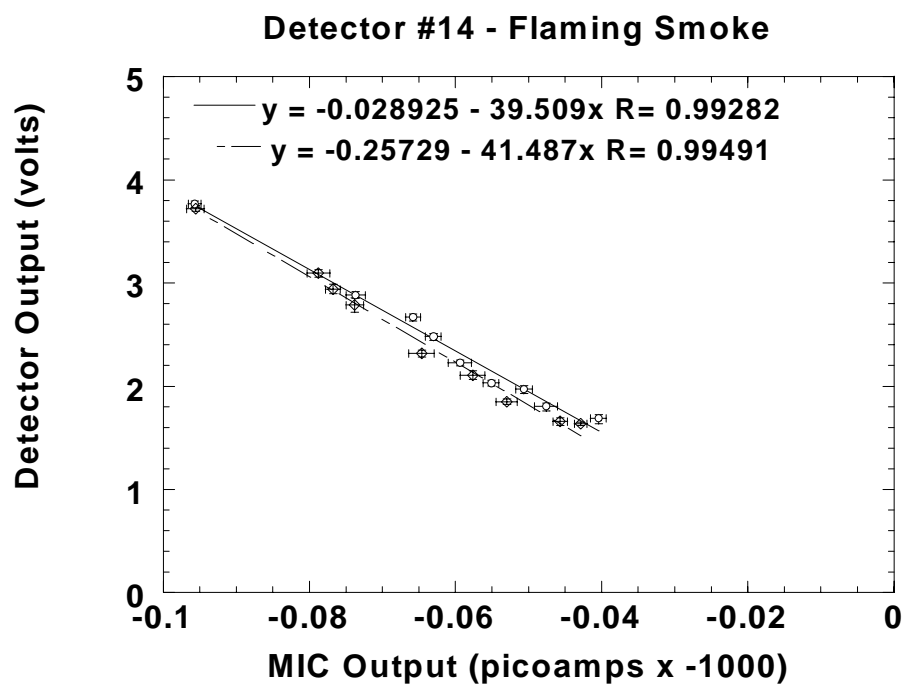Figure 2. Ionization detector calibrations for cotton smoke exposure

Figure 3. Ionization detector calibrations for flaming smoke exposure

Attachment B
Residential Smoke Alarm Tests
Measurement and Data Analysis Plan
Richard W. Bukowski
Jason D. Averill
Building and Fire Research Laboratory
Fire Safety Systems Group

Background

Smoke detectors are the primary life safety strategy for occupants in the event of an unwanted residential fire. As the number of residential fire deaths (about 3000) far outpaces the number of commercial and industrial fire deaths (just over 100 in all non-residential structure fires) it is crucial to understand the level of safety provided by smoke detectors in the residential environment. In 1975, the Illinois Institute of Technology Research Institute (IITRI) and Underwriters Laboratories, Inc (UL), with funding from the National Bureau of Standards (NBS, now the National Institute of Standards and Technology (NIST)), evaluated the performance of commercially available smoke detectors in 76 residential fire experiments representative of the major fatal fire scenarios of the time, in actual homes scheduled for demolition. The purpose of the project, known as the Indiana Dunes Tests, was to evaluate the 'siting and sensitivity requirements for fire detectors to protect residential occupancies.' [i] The tests became the basis for the siting and response characteristics of residential smoke detectors, worldwide.

Since 1975, however, the materials and construction of contents that represent the major combustible items in a typical residential structure have changed ,and the response characteristics of current smoke detectors have also changed as the technology matured. Thus, a systematic evaluation of current residential smoke detector requirements is again considered necessary. The United States Consumer Product Safety Commission (CPSC), the United States Fire Administration (USFA), the Centers for Disease Control and Prevention (CDC), the United States Department of Housing and Urban Development (HUD), Underwriters Laboratories, Inc. (UL), the National Fire Protection Association (NFPA), and the National Research Council Canada (NRCC), in conjunction with NIST's Building and Fire Research Laboratory (BFRL), have joined forces to evaluate the current state of residential smoke detector requirements.

The concept will be to again conduct full-scale tests of current smoke alarm technology in actual homes with actual contents items as fuels. Fire scenarios (including ignition source, first item ignited, room of origin, time of day and season that affect occupant location and building condition) will be selected based upon a statistical analysis of National Fire Incident Reporting System (NFIRS) data. The National Fire Protection Association will be responsible for determining the most risk significant residential fire scenarios for testing. Selected residential fires may include a mattress fire in a bedroom, sofa fire in a living area, and/or a stove fire in a kitchen.

The purpose of this paper is to discuss the measurement equipment and data analysis techniques to be used to analyze data from the smoke detector experiments and to support the project conclusions. The main objective of the experiments is to quantify the available safe egress time which occupants of a residential structure may have in order to evacuate. This will require both

careful measurement of environmental conditions within the structure, as well as sophisticated analysis of the data in order to draw scientifically defensible conclusions. This report will describe both the data acquisition and the data analysis anticipated within the scope of the project. Readers interested in a general overview of large-scale fire testing data collection and analysis are referred to Peacock and Babrauskas.[ii]

Measurement

Fire produces heat, smoke, and toxic gases, all of which can threaten human life. In the experiments we measure the environmental parameters that have an impact on the human and smoke detector response. These parameters include temperature rise, smoke production, and toxic gas production. Aspects of these that can be measured directly include the optical density, number concentration, and mass density of smoke, temperature, mass loss rate, smoke detector and sprinkler response, and species concentrations, including CO, CO_2, O_2, HCl, HCN, NOx, HBr, and HF. Each of these quantities will be discussed below.

Temperature

Temperature measurements will be accomplished using small diameter, bare-bead thermocouples. Thermocouple trees that consist of thermocouples spaced evenly from floor to ceiling provide a measure of vertical temperature stratification and are used to estimate flow through openings. Trees will be arranged throughout the room of origin, as well as various points along the path of occupant egress to provide temperature distributions versus time.

Smoke Detector Response

Smoke detector response will be measured by direct recording of the voltage signal from both ionization and photoelectric smoke detectors arranged for analog output, instead of the more common alarm threshold. By recording analog output the performance of smoke detectors at any desired threshold setting as well as the potential use of algorithms that reduce nuisance alarms can be evaluated. The analog signal will be calibrated against unmodified detectors in the laboratory to verify that the modifications did not affect the detector performance. Detectors will be located in typical, code-required locations, as well as in the room of origin, in order to determine the cost effectiveness of alternative siting rules including a detector in every room.

Sprinkler Response

Residential sprinklers have made significant market penetration in multi-family housing and the current codes require that smoke alarms and sprinklers both be provided independent of each other. This is not necessarily the most effective arrangement but no data exist that demonstrate the performance of the combination. Sprinkler response will be measured using an air pressurized (so called tell-tale) sprinkler. A small quantity of water at the sprinkler head provides an appropriate thermal sink. Upon activation, the pressure in the sprinkler line drops to ambient and the activation time is recorded. In one test, a functional wet sprinkler system will be provided to interact with the fire in the room of fire origin to determine the interplay between the sprinkler, smoke detector, and evacuating occupants.

Mechanical Heat Detector Response

Mechanical heat detectors will be located in the room of origin in compliance with normal practice. Activation will be recorded by the acoustic signal emitted by the device for evaluation

of their performance in conjunction with fewer smoke alarms. [The use of heat detectors in other areas of the house may be useful. As indicated in an April 2000 NFPA report, "The U.S. Fire Problem Overview Report," 50% of deaths and 51.2% of civilian injuries (dwellings and apartments) result from fires in 1) living room, family room or den, 2) kitchen, 3) heating equipment room, and 4) laundry room or area. These areas, along with garages, are not mandated to have detection. The possible benefit of heat detectors in some of these areas (including garages) will be investigated.

Mass Loss Rate
Mass loss rate from the object of fire origin will be recorded using a floor-mounted load cell apparatus. As the object of fire origin is consumed by the fire, the mass decreases. The mass will be measured over time, yielding the instantaneous mass loss rate, as well as the total mass consumed by the fire. Mass loss rate is directly correlated with product yields (toxic species, smoke, etc.), as well as heat release rate.

Heat Release Rate
While heat release rate cannot easily be measured in the field, it can be extracted by either assuming an average heat of combustion for the fuel and multiplying that by the recorded mass loss rate, or by taking an enthalpy balance at the door leading from the room of fire origin. Data for the heat of combustion of typical residential fuels is generally available in the Society of Fire Protection Engineers' *Handbook of Fire Protection Engineering* [iii], although the uncertainty is relatively large as a result of variance within fuel classes. An enthalpy balance through the door of the room of fire origin yields uncertainty due to the possibility of leakage from the room and the individual uncertainty of the inputs to the calculation (temperature, velocity, etc.). Total leakage area for the test building will be measured before the experiments begin using standard, building pressurization techniques.

Optical Density
Optical density will be measured using laser-based light extinction measurement trees. A laser beam's signal strength is measured over time. As smoke passes through the laser beam, the smoke absorbs and reflects a fraction of the light, reducing the light level at an in-line receiver. The correlation between laser beam signal strength and optical density is well characterized. This is the same principle on which some photoelectric smoke detectors operate. Optical density will be measured near smoke detectors, in the room of origin, and along the egress path. Smoke density in the egress path is correlated with walking speed and the occurrence of a psychological barrier to egress in fires.[iv]

Smoke Properties
Smoke properties other than optical density will be measured in selected tests using common fuel packages. Particle number density will be measured using a condensation nucleus counter. Here, an air sample is passed through a humidification stage using either water or alcohol (depending upon the characteristics of the smoke) and then into a chamber in which the pressure is suddenly dropped. The water (or alcohol) condenses on the smoke particles, making them large enough to measure optically.

Mass concentration will be measured using TEOM (Tapered Element Oscillating Microbalance). The TEOM employs a filter of known weight, attached to the end of a pendulum, which oscillates at a base frequency dependent on the initial weight of the filter. An air sample at known flow rate is passed through the filter. As particles collect on the filter, the mass increases, changing the pendulum frequency.

Finally, the size distribution of the smoke will be measured using a cascade impactor. A cascade impactor is a series of stages consisting of a perforated plate spaced at a specific distance from a filter, with the stages stacked one atop the other. At each stage particles larger than a certain value cannot make the turn and impact on the filter. As each filter traps all particles larger than a specific size, weighing each filter yields an integrated total quantity of smoke at discrete sizes. This yields a geometric size distribution.

Primary Gas Analysis - CO, CO$_2$, O$_2$
Measurement of *CO, CO$_2$, and O$_2$* will be performed with NDIR (Nondispersive Infrared) analysis. NDIR works on the principle that a gas species will absorb infrared light at a known wavelength. These instruments are carefully designed to avoid absorption bands that are near those of strong interfering bands such as those of water. See Link, et al for further details of the NDIR technique.[v]

Secondary Gas Analysis - HCl, HCN, NOx, HBr, and HF
The secondary gas measurement will be performed by representatives from National Research Council of Canada using FTIR (Fourier Transform Infrared) techniques. FTIR is a technique similar in principle but different in application as NDIR. See Baxter, et al. for a further discussion of FTIR techniques.[vi]

Additional Measurements
Additional measurements germane to the experiments include detailed documentation of all building geometry and a pressurization test to determine the total leakage in the structure. The pressurization test involves placing a fan in the main entrance to the structure and pressurizing the connected spaces. The flow through the fan is equal to the leakage of the structure.

Velocity
Air velocity in the vicinity of the smoke alarms is important to the analysis of their response since it carries the smoke through the outer housing to the sensor. The most common way of measuring velocity in fire experiments is with bidirectional velocity (Pitot) probes.[vii] These have the advantage that they are robust and insensitive to the angle of the flow vector but they have poor resolution in the range of velocities of interest to detector performance and are noisy. Another technique is hot wire (or film) anemometry, that is more accurate in the range of flows of interest but are affected by soot depositing on the sensing element. BFRL has laser Doppler velocimetry (LDV) equipment that can be used to measure ambient flows but cannot be employed in a fire environment. [viii]This measurement is sufficiently important that the investigators will need to explore available techniques to identify those that will give the best data.

Data Analysis
Data analysis will convert measurement data into meaningful engineering parameters. Quantities such as heat release rate, layer height, and smoke production rates cannot be easily measured outside of the laboratory and require significant data analysis. Table 1 summarizes the engineering parameters to be reported at the conclusion of the Dunes II experiments.

Property	Reported Units
Temperature	°C
Time to Smoke/Heat Detector Activation	s
Time to Sprinkler Response	s
Heat Release Rate	kW
Optical Density of Smoke	m^{-1}
Number Density of Smoke	particles / m^3
Mass Concentration of Smoke	kg / m^3
Size Distribution	nm or m
Gas Analysis	ppm or volumetric percent
Layer Height	m
Leakage	air changes / hour[flow rate and effective leakage area]
Velocity	m/s

Layer height will be calculated using two methods: Cooper's layer height algorithm [ix] and use of the laser based light extinction devices. Heat release rate will be estimated using an enthalpy balance at the door, as well as multiplying the measured mass loss rate by the estimated heat of combustion for the material burning.

One of the primary goals is to determine the time to untenable conditions. The time will vary depending upon which room the measurements are taken and how far away from the fire source the measurements are. Tenability criteria suggested by Purser are detailed below. The criteria will be applied along the path of occupant egress and compared to estimated occupant egress times to evaluate whether the occupants will exit the structure before the onset of untenable conditions.

The choice of tenability criteria can have a significant effect on the judging the time to the untenability of a compartment or space. This section provides an example of the impact of using different tenability criteria on the calculated available safe egress time. All of these are based on extensive research in the effects of heat and toxic gases on persons exposed to a fire environment.[x]

The following criteria are proposed [xi]:

· **Elevated temperature:** When a person is subjected to an upper layer (layer height æ5 ft (1.5 m)) and the average upper layer air temperature exceeds 150 _F (65 _C), the occupant will be assumed to become incapacitated.

· **Smoke obscuration:** An optical density greater than or equal to 0.5 <u>and</u> an interface height less than or equal to 1.0 m is considered the point of occupant incapacitation.

· **Convected heat:** Purser provides a tenability criterion for exposure of humans to elevated temperatures and high humidity. Based on data for hyperthermia (exposure to moderately elevated temperatures for longer periods of time) and skins burns (shorter exposure to higher temperatures), he recommends the following criterion:

$$F_{Ih} = \frac{1}{\exp\left(5.1849 - 0.0273T(^\circ C)\right)}$$

where T is the gas temperature and the fractional incapacitating dose due to heat (F_{Ih}) reaches a value of 1.0 at incapacitation.

· **Toxic gases:** For exposure to elevated gas concentrations, Purser includes the effects of CO, HCN, reduced O_2, and CO_2 and expresses the resulting tenability criterion again as a fractional incapacitating dose due to narcotic gases, F_{IN}:

$$F_{IN} = \max\left(\left(\left(F_{Ico} + F_{Icn}\right) \times VCO_2 + F_{Io}\right), F_{Ico_2}\right)$$

where the individual terms are calculated as integrated quantities over time, defined by Purser for each minute of exposure as:

$$F'_{ICO} = \left(8.2925 \times 10^{-4} \times \text{ppm CO}^{1.036}\right)/30$$
$$F'_{Icn} = 1/\exp\left(5.396 - 0.023 \times \text{ppm HCN}\right)$$
$$VCO_2 = \exp\left(0.193 \times \%CO_2 + 2.004\right)/7.1$$
$$F'_{IO} = 1/\exp\left(8.13 - 0.54\left(20.9 - \%O_2\right)\right)$$
$$F'_{ICO2} = 1/\exp\left(6.1623 - 0.5189 \times \%CO_2\right)$$

where the F'_I terms refer to the per minute exposure dose for CO, HCN, O_2, and CO_2, respectively.

Different tenability criteria will become the determining criteria depending upon the fire scenario. A smoldering fire may incapacitate occupants with toxic gases, while a fast growing fire may incapacitate with heat and/or smoke.

Conclusions
The preceding measurement and data analysis plan will provide statistically significant data addressing the current state of smoke detector efficacy in residential structures. Technical comments regarding the proposed measurements or data analysis techniques should be addressed to:

Richard W. Bukowski.
Building and Fire Research Laboratory
National Institute of Standards and Technology
Building 224, Room A-249, Stop 8642
Gaithersburg, MD 20899-8642

---

[i] Bukowski, R. W., Waterman, T. E., and Christian, W. J. "Detector Sensitivity and Siting Requirements for Dwellings: A Report of the NBS 'Indiana Dunes Tests.'" NFPA No. SPP-43. Nat. Fire Prot. Assn., Quincy, MA, 1975.

[ii] Peacock, R. D. and Babrauskas, V. "Analysis of Large-scale Fire Test Data." Fire Safety Journal 17 (1991) pp. 387 - 414.

[iii] The SFPE Handbook of Fire Protection Engineering, 2nd Ed. P. J. DiNenno, Editor. Nat. Fire Prot. Assoc., Quincy, MA, 1995.

[iv] Jin, T. "Visibility Through Fire Smoke, Part 5. Allowable Smoke Density for Escape From Fire." Report of Fire Research Institute of Japan, No. 42, 12-18, September 1976.

[v] Link, W. T., McClatchie, E. A., Watson, D. A., and Compher, A. B. "A Fluorescent Source NDIR Carbon Monoxide Analyzer. 12th Conference on Methods in Air Pollution and Industrial Hygiene Studies. 6 - 8 April, 1971.

[vi] Baxter, L. L.; Sclippa, G. C.; Slami, A. J.; Richards, G. H.; Ottesen, D. K.; Harb, J. N. "FTIR Emission Spectroscopy Applied to In Situ, Real-Time, Surface Chemistry Measurements." Sandia Combustion Research Technical Review, Sandia National Laboratories (1995) pp. 90-91.

[vii] McCaffrey, B. J. and Heskestad, G. "Robust Bidirectional Low-Velocity Probe for Flame and Fire Application." Combustion and Flame, Vol. 26, No. 1, 125-127, February 1976.

[viii] Frenklach, M., Taki, S., Li Kwok Cheng, C. K., and Matula, R. A. "LDV Measurement of Soot Particle Size." Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. Technical Meeting, 1982. Co-Hosted by: AeroChem Research Laboratories, Inc. and Princeton University. December 14-16, 1982, Atlantic City, NJ, 16/1-4 pp, 1983.

[ix] Cooper, L.Y., Harkleroad, M., Quintiere, J. G., and Rinkinen, W. J. "An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multiroom Fire Scenarios." J. Heat Trans., 104 (1982) pp. 741 - 749.

[x] Purser, D. A. "Toxicity Assessment of Combustion Products in SFPE Handbook of Fire Protection Engineering, 2nd Edition." Ed. by DiNenno, et. al. National Fire Protection Association, Quincy, MA, 1995, pp. **2**-85 - **2**-146.

[xi] Gann, R. G., V. Babrauskas, R. D. Peacock, J. R. Hall, Jr., "Fire Conditions for Smoke Toxicity Measurement." Fire and Materials, Col. 18, No. 3, 193-199, 1994.